Phenomenology of $f_0(980)$ photoproduction on the proton at CLAS energies

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In this work we present the results of a theoretical analysis of the data on photoproduction of $f_0(980)$ meson in the laboratory photon energy between 3.0 and 3.8 GeV. A comparison is done to the measurements performed by the CLAS collaboration at JLab accelerator for the exclusive reaction $\gamma p \to p f_0(980)$. In the analysis the partial S-wave differential cross section is described by a model based on Regge approach with reggeized exchanges and distinct scenarios for the $f_0(980) \to V\gamma$ coupling are considered. It is shown that such a process can provide information on the resonance structure and production mechanism.

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I. INTRODUCTION

The spectroscopy of the low mass scalar mesons, like the $f_0(980)$ one, is an exciting issue in hadronic physics and is still an unsettled question. The topic is quite controversial as the mass spectrum ordering of low-lying scalar mesons disfavours the usual quark-antiquark picture and a window is opened to a prolific investigation of the topic. For instance, in the past years the low mass states $J^{PC} = 0^{++}$ have been considered quark-antiquark mesons [1], tetraquarks [2], hadron molecules [3], glueballs and hybrids [4, 5]. Such a conflicting interpretation comes from the fact the situation is complex in low energies where quantitative predictions from QCD are challenging and rely mostly on numerical techniques of lattice QCD. Nowadays, theoretical analysis consider also the gluonic degrees of freedom as the glueball resonance with no quarks having not exotic quantum numbers and that cannot be accommodated within quark-antiquark nonets [6]. In this context, the photoproduction of exotic mesons [7] can be addressed using arguments based on vector meson dominance where the photon can behave like an $S = 1$ quark-antiquark system. Therefore, such a system is more likely to couple to exotic quantum number hybrids. Such a process could provide an alternative to the direct observation of the radiative decays at low energies. Along those lines, the GlueX experiment [8] is being installed and its primary purpose is to understand the nature of confinement in QCD by mapping the spectrum of exotic mesons generated by the excitation of the gluonic field binding the quarks.

The gluonic content of mesons could be directly tested in current accelerators in case a clear environment be available. In the limit of very high energies the exclusive exotic meson production in two-photon and Pomeron-Pomeron interactions in coherent nucleus-nucleus collisions at high energy colliders can be easily computed. In these cases, the photon flux scales as the square charge of the beam, Z^2, and then the corresponding cross section is highly enhanced by a factor $\propto Z^4 \approx 10^7$ for gold or lead nuclei at RHIC and LHC, respectively. A competing channel, which produces similar final state configuration, is the central diffraction process that is modeled in general by two-Pomeron interaction. For instance, in Ref. [9] the cross sections for these two channels are contrasted in the production of glueball candidates like the low-lying scalar mesons. The cross sections were sufficiently large for experimental measurement and the event rates can be obtained using the beam luminosity [10] for LHC which produces $5 \cdot 10^5$ events for $f_0(1500)$ mesons in the two-photon channel whereas the integrated cross section for exclusive diffractive process is around 500 μb. The central diffractive production of mesons $f_0(980)$ and $f_2(1270)$ at the energy of CERN-LHC experiment on proton-proton collisions was further investigated in Ref. [11]. The processes initiated by quasi-real photon-photon collisions and by central diffraction processes were also considered. The main motivation is that ALICE collaboration has recorded zero bias and minimum bias data in proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 7$ TeV. Among the relevant events, those containing double gap topology have been studied and they are associated to central diffractive processes [12]. In particular, central meson production was observed. In the double gap distribution, the K_s^0 and ρ^0 are highly suppressed while the $f_0(980)$ and $f_2(1270)$ with quantum numbers $J^{PC} = (0,2)^{++}$ are much enhanced. Such a measurement of those states is evidence that the double gap condition used by ALICE selects events dominated by double Pomeron exchange. The main predictions of Ref. [11] are the exclusive diffractive cross section for $f_0(980)$ being $d\sigma(y = 0)/dy \simeq 27$ μb and coherent pp cross section $\sigma_{\gamma\gamma} = 0.12$ nb at $\sqrt{s}_{pp} = 7$ TeV.

As far the low energy regime is concerned, in Ref. [13] we studied the photoproduction of the $a_0(980)$, $f_0(1500)$ and $f_0(1710)$ resonances for photon energies relevant for the GlueX experiment at $E_\gamma = 9$ GeV using current ideas on glueball and $q\bar{q}$ mixing. The meson differential and integrated cross sections were evaluated and the effect of distinct mixing scenarios were investigated. Although large backgrounds were expected, the signals could be visible by considering only the all-neutral channels, that

is their decays on $\pi^0\pi^0$, $\eta^0\eta^0$ and $4\pi^0$. The theoretical uncertainties were still large, with $f_0(1500)$ the more optimistic case.

Here, we investigate the photoproduction of meson state $f_0(980)$ and distinct scenarios for the $f_0(980) \to V\gamma$ coupling are considered. We focus on the S-wave analysis on the forward photoproduction. The theoretical formalism employed is the Regge approach with reggeized ρ and ω exchange [13]. This assumption follows from Regge phenomenology where high-energy amplitudes are driven by t-channel meson exchange. This paper is organized as follows: in next section we present the relevant scattering amplitudes and how they are related to the differential cross sections. In last section numerical results are presented and parameter dependence is addressed and comparison to the CLAS data for direct photoproduction of $f_0(980)$ is also done. Finally, the conclusions and discussions follow at the end of section.

II. MODEL AND CROSS SECTION CALCULATION

We focus on the S-wave analysis of nondiffractive $f_0(980)$ photoproduction. Acording to the Regge phenomenology, one expects that only the t-channel meson exchanges are important in such a case. The ρ and ω reggeized exchanges are to be considered in the present analysis. To obtain mass distribution for the scalar $f_0(980)$ meson, one represents it as relativistic Breit-Wigner resonance with energy-dependent partial width. The differential cross section for the production of a scalar with invariant mass M, and its decay to two pseudoscalars, masses m_a and m_b, can be written as,

$$\frac{d\sigma}{dt\,dM} = \frac{d\hat{\sigma}(t,m_S)}{dt}\frac{2m_S^2}{\pi}\frac{\Gamma_i(M)}{(m_S^2-M^2)^2+(M\Gamma_{\rm Tot})^2}, \quad (1)$$

where $d\hat{\sigma}/dt$ is the narrow-width differential cross section at a scalar mass $M = m_S$ and $\Gamma_i(M)$ being the pseudoscalar-pseudoscalar final states the partial width, which can be computed in terms of the SPP coupling g_i. A note is in order at this point. Although the main decay of the $f_0(980)$ is $\pi\pi$, this state resides at the $K\bar{K}$ threshold. Therefore, following Ref. [7] we use the Breit-Wigner parametrisations obtained in the analysis of ϕ radiative decays [14]. In such a case, the Breit-Wigner width takes the form

$$\begin{aligned}\Gamma(M) &= \frac{g_{\pi\pi}^2}{8\pi M^2}\sqrt{\frac{M^2}{4}-M_{\pi\pi}^2}\\ &+ \frac{g_{K\bar{K}}^2}{8\pi M^2}\left[\sqrt{\frac{M^2}{4}-M_{K^+K^-}^2}+\sqrt{\frac{M^2}{4}-M_{K^0\bar{K}^0}^2}\right],\end{aligned}$$

where we set the following parameters: $M = 984.7$ MeV, $g_{K\bar{K}} \equiv g_{K^+K^-} = g_{K^0\bar{K}^0} = 0.4$ GeV, $g_{\pi^+\pi^-} = \sqrt{2}g_{\pi^0\pi^0} = 1.31$ GeV for the scalar meson $f_0(980)$ considered here.

Let us proceeding, the reaction proposed here is $\gamma p \to p\, f_0(980)$. Within the Regge phenomenology the differential cross section in the narrow-width limit for a meson of mass m_S is given by [13],

$$\frac{d\hat{\sigma}}{dt}(\gamma p\to pM) = \frac{|\mathcal{M}(s,t)|^2}{64\pi\,(s-m_p^2)^2}, \quad (2)$$

where $\mathcal{M}$ is the scattering amplitude for the process, s, t are usual Mandelstan variables and m_p is the proton mass. For the exchange of a single vector meson, i.e. ρ or ω one has:

$$\begin{aligned}|\mathcal{M}(s,t)|^2 &= -\frac{1}{2}\mathcal{A}^2(s,t)\Big[\,s(t-t_1)(t-t_2)\\ &\qquad +\frac{1}{2}t(t^2-2(m_S^2+s)t+m_S^4)\Big]\\ &- \mathcal{A}(s,t)\mathcal{B}(s,t)m_p s(t-t_1)(t-t_2)\\ &- \frac{1}{8}\mathcal{B}^2(s,t)s(4m_p^2-t)(t-t_1)(t-t_2). \quad (3)\end{aligned}$$

where t_1 and t_2 are the kinematical boundaries

$$\begin{aligned}t_{1,2} &= \frac{1}{2s}\left[-(m_p^2-s)^2+m_S^2(m_p^2+s)\right.\\ &\pm \left.(m_p^2-s)\sqrt{(m_p^2-s)^2-2m_s^2(m_p^2+s)+m_S^4}\,\right], \quad (4)\end{aligned}$$

and where one uses the standard prescription for Reggeising the Feynman propagators assuming a linear Regge trajectory $\alpha_V(t) = \alpha_{V0} + \alpha_V' t$ for writing down the quantities $\mathcal{A}(s,t)$ and $\mathcal{B}(s,t)$:

$$\begin{aligned}\mathcal{A}(s,t) &= g_A\left(\frac{s}{s_0}\right)^{\alpha_V(t)-1}\frac{\pi\alpha_V'}{\sin(\pi\alpha_V(t))}\frac{1-e^{-i\pi\alpha_V(t)}}{2\,\Gamma(\alpha_V(t))},\\ \mathcal{B}(s,t) &= -\frac{g_B}{g_A}\,\mathcal{A}(s,t). \quad (5)\end{aligned}$$

It is assumed non-degenerate ρ and ω trajectories $\alpha_V(t) = \alpha_V(0) + \alpha_V' t$, with $\alpha_V(0) = 0.55\,(0.44)$ and $\alpha_V' = 0.8\,(0.9)$ for ρ (ω). In Eq. (5) above, one has that $g_A = g_S(g_V + 2m_p g_T)$ and $g_B = 2g_S g_T$. The quantities g_V and g_T are the VNN vector and tensor couplings, g_S is the γVN coupling. For the ωNN couplings we have set $g_V^\omega = 15$ and $g_T^\omega = 0$ [13] and for the ρNN couplings we used $g_V^\rho = 3.4$, $g_T^\rho = 11$ GeV^{-1}. The $SV\gamma$ coupling, g_S, can be obtained from the radiative decay width through [15]

$$\Gamma(S\to\gamma V) = g_S^2\frac{m_S^3}{32\pi}\left(1-\frac{m_V^2}{m_S^2}\right)^3. \quad (6)$$

In case of f_0 meson being considered as mixed $n\bar{n}$, $s\bar{s}$ and glueball states their radiative decays to a vector meson are expected to be highly sensitive to the degree of mixing between the $q\bar{q}$ basis and the glueball [16]. In Ref. [13] three distinct mixing scenarios were considered. The first one is the bare glueball being lighter than the bare $n\bar{n}$ state; the second scenario corresponds to the

Scenario	$f_0(980) \to \gamma V$
1	83 (9.2)
2	125 (14)
3	1005 (463)

TABLE I: *The widths, $\Gamma(S \to \gamma V)$, for the radiative decays of the scalar mesons to vector mesons $V = \rho\,(\omega)$ in units of keV. These results was extracted from Ref. [7] for scenario 1, from Ref. [15] for scenario 2 and from Ref. [17] for scenario 3.*

glueball mass being between the $n\bar{n}$ and $s\bar{s}$ bare state and finally the third one where glueball mass is heavier than the bare $s\bar{s}$ state. The numerical values for the widths having effects of mixing on the radiative decays of the scalars on ρ and ω can be found in Table 1 of Ref. [13]. It is clear that the width is strongly model dependent and different approaches can be taken into account. For instance, we quote the work in Ref. [17], where the decays of a light scalar meson into a vector mesons and a photon, $S \to V\gamma$, are evaluated in the tetraquark and quarkonium assignements of the scalar states. The coupling now reads,

$$\Gamma(S \to \gamma V) = g_S^2 \frac{(m_S^2 - m_V^2)^3}{8\,\pi\, m_S^3}. \tag{7}$$

The different nature of the couplings corresponds to distinct large-N_c dominant interaction Lagrangians. In next section we compare those approaches discussed above for the direct $f_0(980)$ photoproduction in the CLAS energies.

III. RESULTS AND DISCUSSIONS

In what follows we present the numerical results for the direct $f_0(980)$ photopproduction considered in present study and the consequence of the different mixing scenarios as well as the tetraquark and quarkonium assignements of the scalar states discussed in previous section. The results presented here will consider three distinct scenarios. In scenarios 1 and 2 the $f_0(980)$ will be interpreted as a ground-state nonet and in scenario 3 as a tetraquark. The g_S coupling can be obtained from the radiative decay width in Table I using Eq. (6) for scenarios 1 and 2 and Eq. (7) for scenario 3. The results for scenarios 1 and 2 in Table I were extracted form Refs. [7, 15] and the differential cross section of photoproduction for $f_0(980)$ obtained in these scenarios are in agreement with CLAS data [18].

We also have considered the results obtained in Tables 3, 4, 6 and 7 of Ref. [17] for radiative decay of $f_0(980)$. The authors have considered this ressonance as tetraquark or quarkonium including or not Vector Meson Dominace. We have tested all of these possibilities to calculate the g_s coupling, which is used to evaluate the differential cross section for $f_0(980)$ photoproduction. The

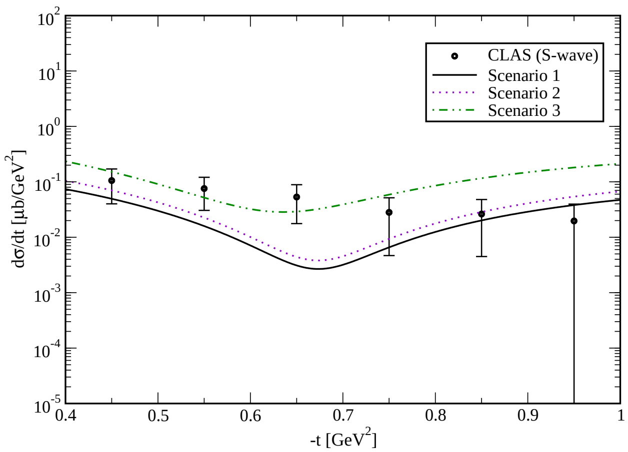

FIG. 1: (Color online) The S-wave differential photoproduction cross section for $f_0(980)$ photoproduction as a function of momentum transfer squared at CLAS experiment energy $E_\gamma = 3.4$ GeV. The statistical/systematic error bars for CLAS data [18] were summed in quadrature.

only possibility which results in a differential cross section within the error bars of CLAS data [18], is presented in Table I (scenario 3). For all other remaining possibilities the differential cross section of photoproduction is larger or smaller than CLAS data by a factor of 50.

The partial S-wave differential cross sections for $f_0(980)$ are presented in Fig. 1 at $E_\gamma = 3.4 \pm 0.4$ GeV and integrated in the $M_{\pi\pi}$ mass range 0.98 ± 0.04 GeV. As a general picture, the typical pattern is a vanishing cross section towards the forward direction due to the helicity flip at the photon-scalar vertex and the dip at $-t \approx 0.7$ GeV^2 related to the reggeized meson exchange. The scenarios 1 and 2 are represented by the solid and dotted lines, respectively. Both of them fairly reproduces the trend of CLAS data. The scenario 3 is denoted by the dot-dashed curve. In this case the result overestimates the last CLAS data points.

The theoretical predictions are compared to the CLAS analysis at Jafferson Lab [18], where the $\pi^+\pi^-$ photoproduction at photon energies between 3.0 and 3.8 GeV has been measured in the interval of momentum transfer squared $0.4 \leq |t| \leq 1.0$ GeV^2. There, the first analysis of S-wave photoproduction of pion pairs in the region of the $f_0(980)$ was performed. The interference between P and S waves at $M_{\pi\pi} \approx 1$ GeV clearly indicated the presence of the f_0 resonance. The exclusive reaction $\gamma p \to p f_0$ was measured through the most sizable decay mode which is $f_0(980) \to \pi^+\pi^-$.

For sake of completeness, in Fig. 2 the S-wave $\pi^+\pi^-$ invariant mass distribution at $E_\gamma = 3.4$ GeV and $|t| = 0.55$ GeV^2. For the theoretical analysis we consider the scenario 1. In this plot we consider two possibilities for the coupling $g_{\pi\pi}$. The first is $g_{\pi\pi} = 1.31$ GeV presented in Ref. [7] and the second $g_{\pi\pi} = 2.3 \pm 2$ GeV presented in Ref. [19]. We also studied the dependence of the invariant mass distribution on the branching ratios for

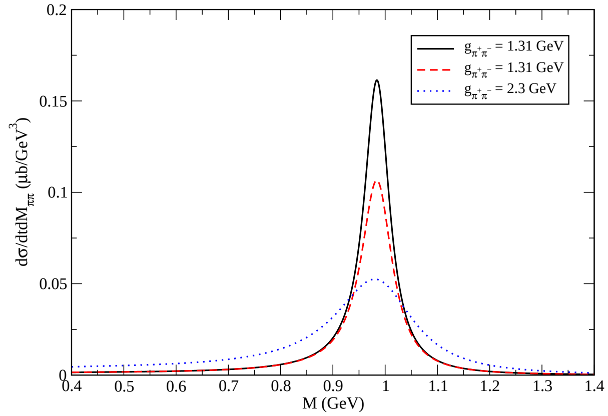

FIG. 2: (Color online) S-wave $\pi^+\pi^-$ invariant mass distribution at $E_\gamma = 3.4$ GeV, $|t| = 0.55$ GeV^2. The results stand for $\Gamma_{f_0\to\pi\pi} = 0.85\,\Gamma_{total}$ (solid and dotted curves) and $\Gamma_{f_0\to\pi^+\pi^-} = 0.46\,\Gamma_{total}$ (dashed curve).

$f_0(980)$ which was used to obtain the total decay width in Eq. (1). It was assumed that the dominant decay of $f_0(980)$ is $\pi\pi$ with the remaining channel $K\bar{K}$. Thus, we present the invariant mass distribution considering $\mathcal{B}(f_0 \to \pi\pi) = (85)\%$ as in Ref. [7] or $\mathcal{B}(f_0 \to \pi^+\pi^-) = 46 \pm 6\%$ as reported recently in Ref. [20]. It is possible to see a strong dependence invariant mass distribution on the coupling constant $g_{\pi\pi}$. An interesting dependence on branching ratios is observed too.

In summary, we have studied the photoproduction of $f_0(980)$ resonance for photon energies considered in the CLAS experiment at Jefferson Lab, $E_\gamma = 3.4 \pm 0.4$ GeV. It provides a test for current understanding of the nature of the scalar resonances and on ideas for glueball and $q\bar{q}$ mixing. We have calculated the differential cross sections as function of effective masses and momentum transfers. The effect of distinct mixing scenarios in the calculation of coupling $S \to V\gamma$ were investigated. Our predictions of the cross sections are somewhat consistent with the experimental analysis from CLAS Collaboration. The present experimental data are able to exclude some possibilities for the $S \to V\gamma$ coupling. We show also the large dependence on the parameters as the $g_{\pi\pi}$ and branching fractions.

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